BLAST RESISTANT CAPACITY OF 12 INCH REINFORCED CONCRETE SUBSTANTIAL DIVIDING WALLS IN ACCORDANCE WITH TM5-1300

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ABSTRACT

Twelve-inch reinforced concrete walls have been constructed for many years within DoD munitions facilities and the commercial explosive industry to limit blast effects from accidental explosions. Such walls are a special category of "Dividing Walls" as defined by DoD explosive safety standards. Specific explosive limits are defined for such existing walls. However use of these walls for new operations or new construction requires performance based on rational methods of structural dynamics given in TM5-1300, "Design of Structures to Resist the Effects of Accidental Explosions". This paper discusses the performance of 12 inch Reinforced concrete walls and provides charts and figures which demonstrate the blast resistant capacity of such walls in several common configurations.

BACKGROUND

Existing Department of Defense (DOD) and related military service explosive safety standards address the utilization of "Dividing Walls" as an acceptable means to subdivide explosive quantities and reduce the maximum credible explosive event for siting and operations. One widely used structural element used to achieve this performance is the 12 inch reinforced concrete wall. Reinforcement provided in such walls is normally number 4 (one-half inch diameter) bars spaced at 12 inches on center, with horizontal and vertical bars on each face of the wall. Figure 1 presents a typical configuration for such a wall. Such dividing walls have been constructed in U.S. military and commercial explosive manufacturing, handling and storage facilities for more than 50 years. They have become a de facto standard. The acceptable use of such walls in facilities is addressed in each of the relevant DoD and service explosive safety standards. The description and application in the individual service standards are similar to the DoD standard. However there are subtle differences. These differences provide "grandfather" relief for existing facilities. Because of the past acceptance of these walls for certain applications, limitations for new operations may be misunderstood.

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SUBSTANTIAL DIVIDING WALL DEFINITIONS

The governing DOD explosive safety standard which service specific standards must comply with is DoD 6055.9 STD (Ref. 1). This document defines a "Dividing Wall" as:

> "A wall designed to to prevent, control, or delay propagation of an explosion between quantities of explosives on opposite sides of the wall".

To "prevent" or "delay" propagation implies both Category III and Category IV protection. Chapter 9 Paragraph B. 2. b. then states that design of dividing walls in accordance with TM5-1300, AFM 88-22, NAVFAC P-397 (Reference 2) will assure the structural performance needed to function as a dividing wall. No additional guidance is given regarding the use of "12 inch reinforced concrete walls" as a special dividing wall case.

Within the Army, at government owned facilities, application of Reference 1 is implemented through AMCR-385-100 (Reference 3). This reference provides a definition of a "Substantial Dividing Wall" as:

> "An interior wall designed to prevent detonation of quantities explosives on opposite sides of the wall".

In this definition, the implication is that Category III protection is provided and is essentially the same as in the DOD standard. Reference 3 then follows in Chapter 5, paragraph 5-6 with criteria to assure this performance:

> "A substantial dividing wall will be designed in accordance with TM5-1300, 'Structures Designed to Resist the Effects of Accidental Explosions', to prevent propagation of detonation by blast and by ammunition or wall fragments."

This definition is again equivalent to Reference 1. However, unlike the DOD standard, AMCR-385-100 also provides additional specific guidance regarding the use of "12 inch reinforced concrete walls". This guidance states:

> "Reinforced Concrete walls not less than 12 inches thick are effective in preventing propagation between bays when the donor quantity does not exceed 425 pounds of class 1, Division 1 explosives ..... In existing buildings having such walls, operations shall be planned ....".

In this definition "prevention of propagation" is apparently intended to imply sufficient time delay such that a subsequent detonation in an adjacent bay will not coalesce with the initial shock wave. This definition provides no discussion of detailed reinforcement requirements for such walls. An important point in the application of this standard is that it recognizes the use of 12 inch reinforced concrete walls in existing buildings to provide separation for 425 pounds. If completely new construction is planned, then it should be designed to comply with Reference 2.

For ammunition and explosive production by DoD contractors, required safety standards are prescribed in DoD Standard 4145.26-M (Reference 4). This document provides a definition of a "Substantial Dividing Wall" as:

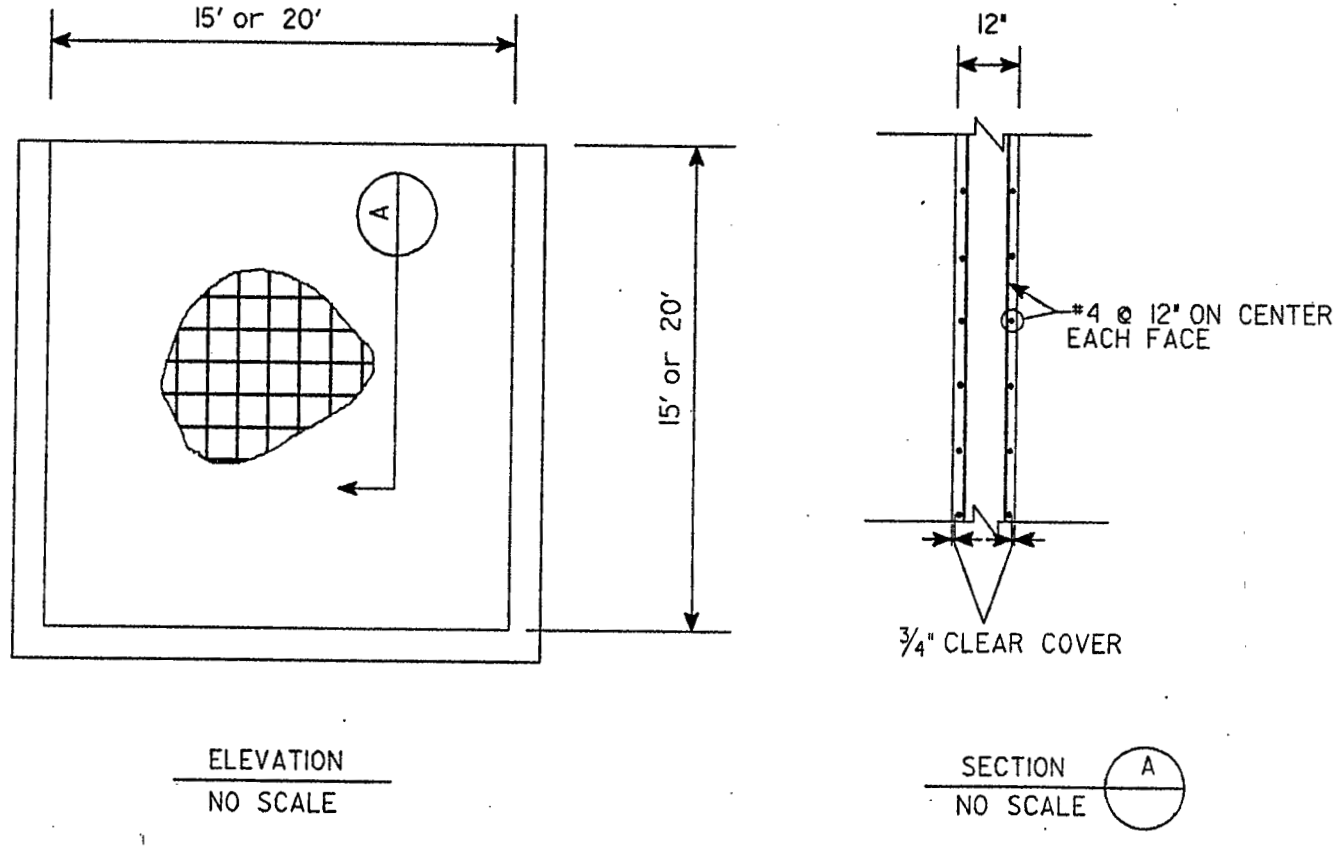


Figure 1- Typical 12" Reinforced Concrete Dividing Wall

> "An interior wall designed to prevent 'simultaneous detonation' of explosives on opposite sides of the wall. However such walls may not prevent propagation".

This definition, while similar to those in References 1 and 3, is the most complete and accurate of the three, recognizing both Category III and IV performance. As with Reference 3, this document also provides specific guidance for the use of "12 inch reinforced concrete" walls.

This guidance is also similar to reference 3 in that it allows use of such walls for bay limits of up to 425 pounds. It is more specific in that it describes in detail the design requirements of such walls:

> "Reinforced concrete walls may vary in thickness, but will be at least 12 inches thick. At a minimum, both faces will be reinforced with rods (deformed reinforcing steel) at least 1/2 inch in diameter. The rods will be spaced at not more that 12 inches on center horizontally and vertically, interlocking with the footing rods and secured to prevent overturning. Rods on one face will be staggered with regards to rods on the opposite face and should be approximately 2 inches from each face. Concrete should have a minimum of 2500psi compressive strength"

A significant difference regarding reference 4 is that it is silent on the issue of the use of this type of walls for "existing" or "new" construction. It seems clear that Reference 3 intended to provide a "grandfather clause" for existing construction. Reference 4 however can be interpreted to allow newly constructed 12 inch reinforced concrete walls to prevent propagation for limits up to 425 pounds per bay. As will be demonstrated, analysis of these walls in accordance with Reference 2 will not allow such limits. To summarize, existing 12 inch reinforced concrete walls are generally recognized as acceptable by current standards for preventing simultaneous detonation (Category IV) for up to 425 pounds of explosive. Most existing walls of this type are reinforced as described by Reference 4. This explosive quantity was arrived at through limited full scale testing involving lightly cased explosives. Analysis in accordance with Reference 2 would not support such a value.

CURRENT APPLICATIONS

Existing facilities, both at government and contractor owned facilities, are continuously being modified to incorporate new production, maintenance or storage missions. These modifications must comply with the latest interpretation of explosive safety regulations. Thus operating conditions for which an existing substantial dividing wall was originally acceptable, may now be unacceptable. An example of this would be a new requirement to assure personnel protection in adjacent bays for operations which are now considered hazardous. The definition of personnel protection in Reference 1 is overpressure not to exceed 2.3 psi and no exposure to fragments with greater than 58 ft-lbs of energy. The 425 pound limit for non-propagation is clearly not compatible with such a personnel protection requirement. These personnel protection limitations are recognized by reference 3 in Chapter 25, paragraph 4 which discusses operational shields. This requirement limits explosive

quantities to 15 pounds when a 12 inch reinforced concrete wall is used to provide personnel protection. This limit has been arrived at through analysis based on reference 2 and is a prescriptive value accepted as providing the desired personnel protection. It should be emphasized that all new construction of dividing walls should comply with the principles of reference 2 to assure the desired protection level.

ANALYSIS OF TYPICAL 12 INCH WALLS

The remainder of this paper will present the results of analysis and discussion of some recent test data on 12 inch reinforced concrete walls. The information presented is sufficiently accurate to provide an insight into the expected performance of such walls. It is not intended to represent an exact structural analysis of the capacity for all such walls. The analysis is based on methods consistent with reference 2.

Reference 2 provides design criteria for maximum wall rotation limits intended to provide personnel protection and to prevent simultaneous propagation. Shown in Table 1 are the limits for various conditions.

TABLE 1 - STRUCTURE FAILURE CRITERIA TM5-1300

SECTION TYPE	SUPPORT ROTATION	
	INCIPIENT FAILURE	MAXIMUM DESIGN ROTATION
FLEXURAL,NO STIRRUPS	2°	1°
FLEXURAL,W/ STIRRUPS	4°	2°

Most existing 12 inch reinforced concrete walls are only lightly reinforced for flexure, and have neither stirrups nor lacing to resist shear. Therefor the 1 degree rotational limit will govern for personnel protection (Category I) and 2 degree rotational limit for non-propagation (Category IV). Spall fragments and overpressures for personnel exposure are treated separately. The response of several typical 12 inch walls will be represented using Pressure-Impulse (P-I) Diagrams for a 2 degree rotation limit. The pressure and impulse capacities for 1 degree rotations are very similar to those for 2 degree rotations. Therefore this paper will use 2 degrees to represent both category I and IV damage. P-I Diagrams describe the approximate pressure and impulse capacity that exist for any structural element given specified limits of rotation. The asymptotes that describe the pressure and impulse limits are connected by a transition region which represents the pressure-time response region. A detailed discussion of P-I Diagrams is found in Reference 5.

Figure 2 through 4 illustrate approximate Pressure-Impulse (P-I) Diagrams for walls with three different boundary conditions; cantilever, two adjacent sides supported and three sides supported. Each figure shows the results for both a 15x15 and a 20x20 foot wall. The data for these figures were derived using Single-Degree-Of-Freedom (SDOF) analysis over a range of donor sizes and stand-offs. Superimposed on these figures are selected explosive quantity curves which allow the user to estimate whether the limiting 2 degree rotation design criteria will be exceeded at the charge weight and stand-off distance being considered. The explosive quantity curves are based on the reflected pressure and impulse data taken from Figure

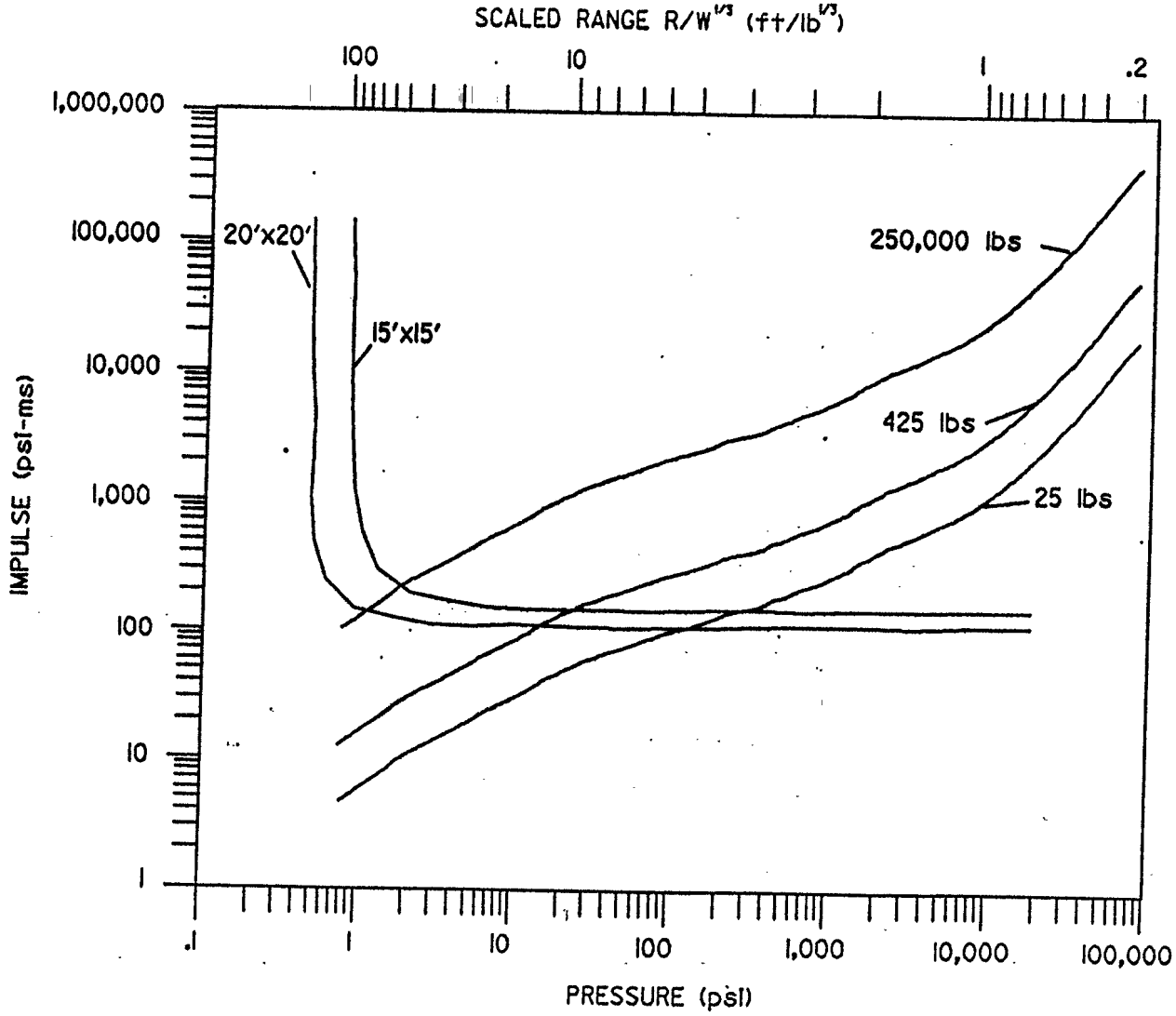


Figure 2 - P-I Diagram for 15 and 20 ft Cantilever Walls

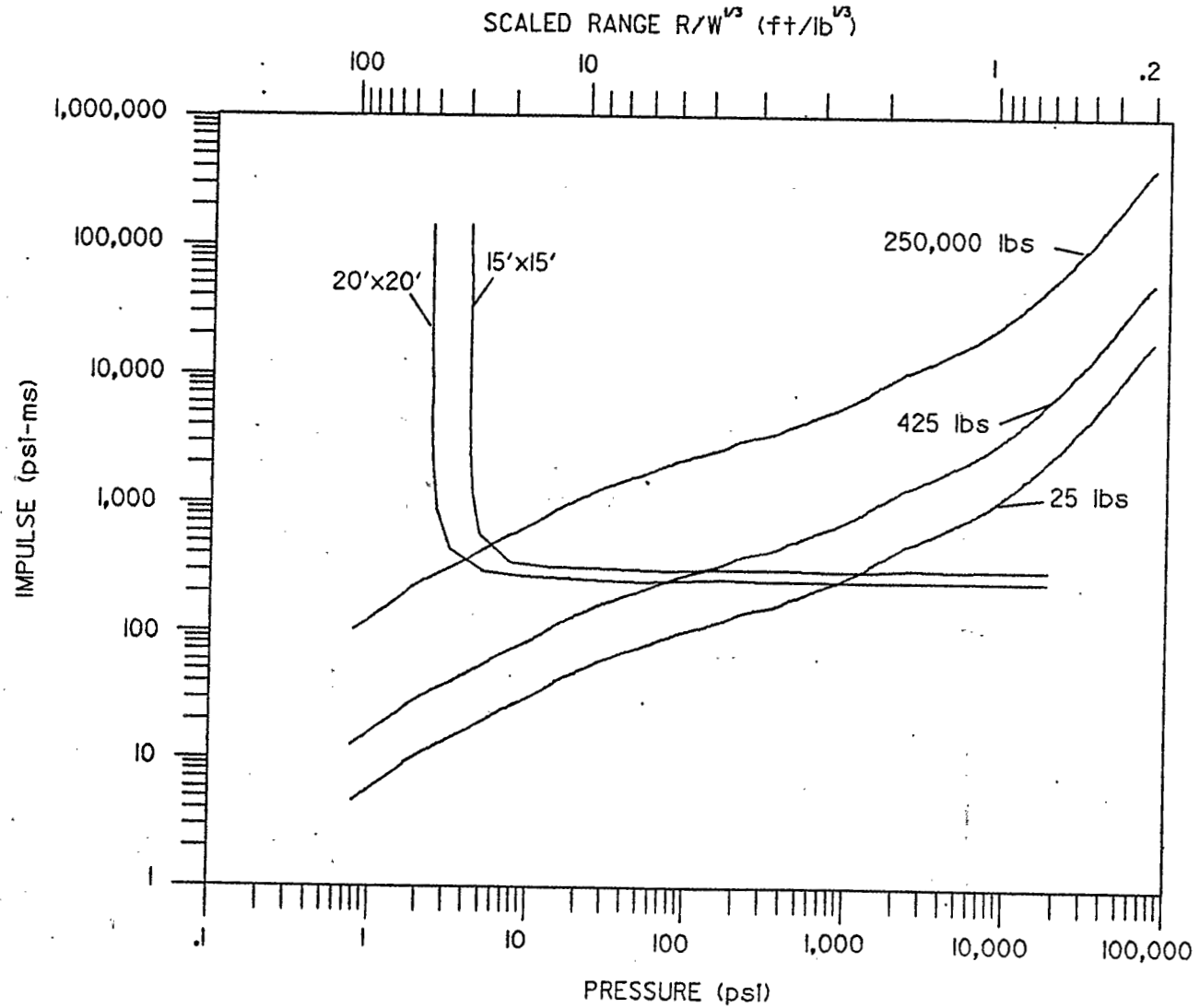


Figure 3 - P-I Diagram for 15 and 20 ft Wall Supported at Base and One Side

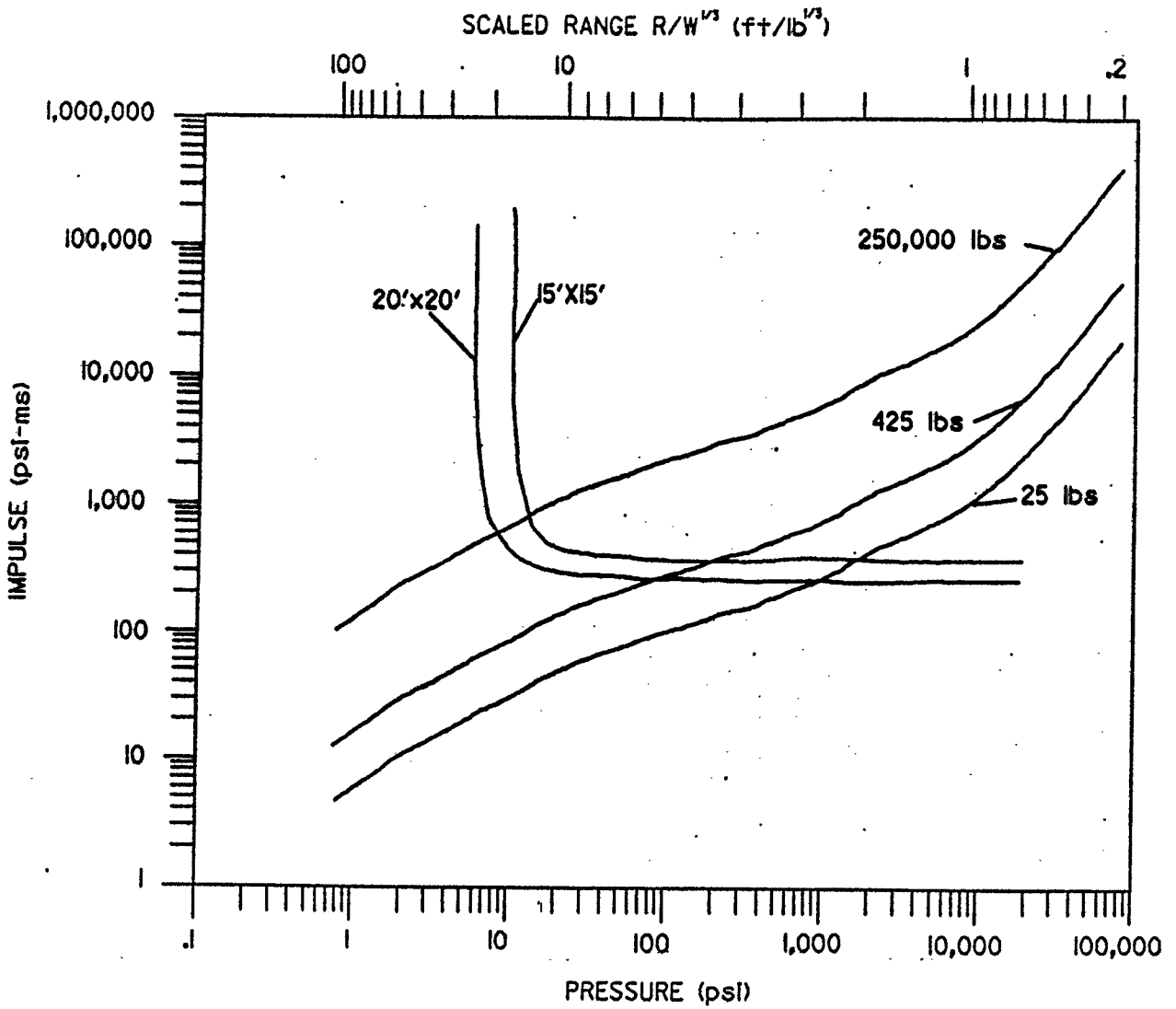


Figure 4 - P-I Diagram for 15 and 20 ft Wall Supported at Base and One Side

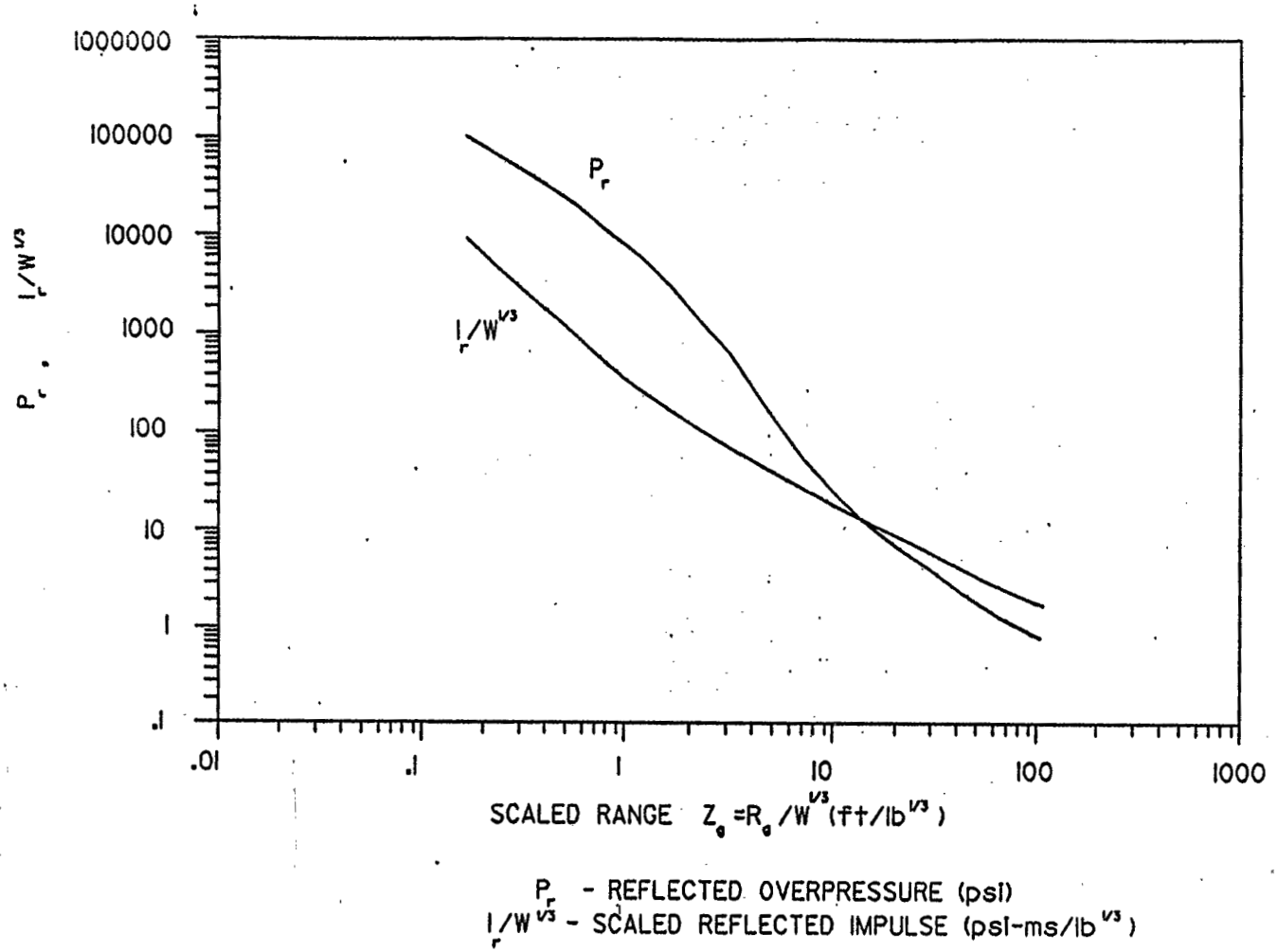


Figure 5 - Scaled Range vs. Pressure and Scaled Impulse

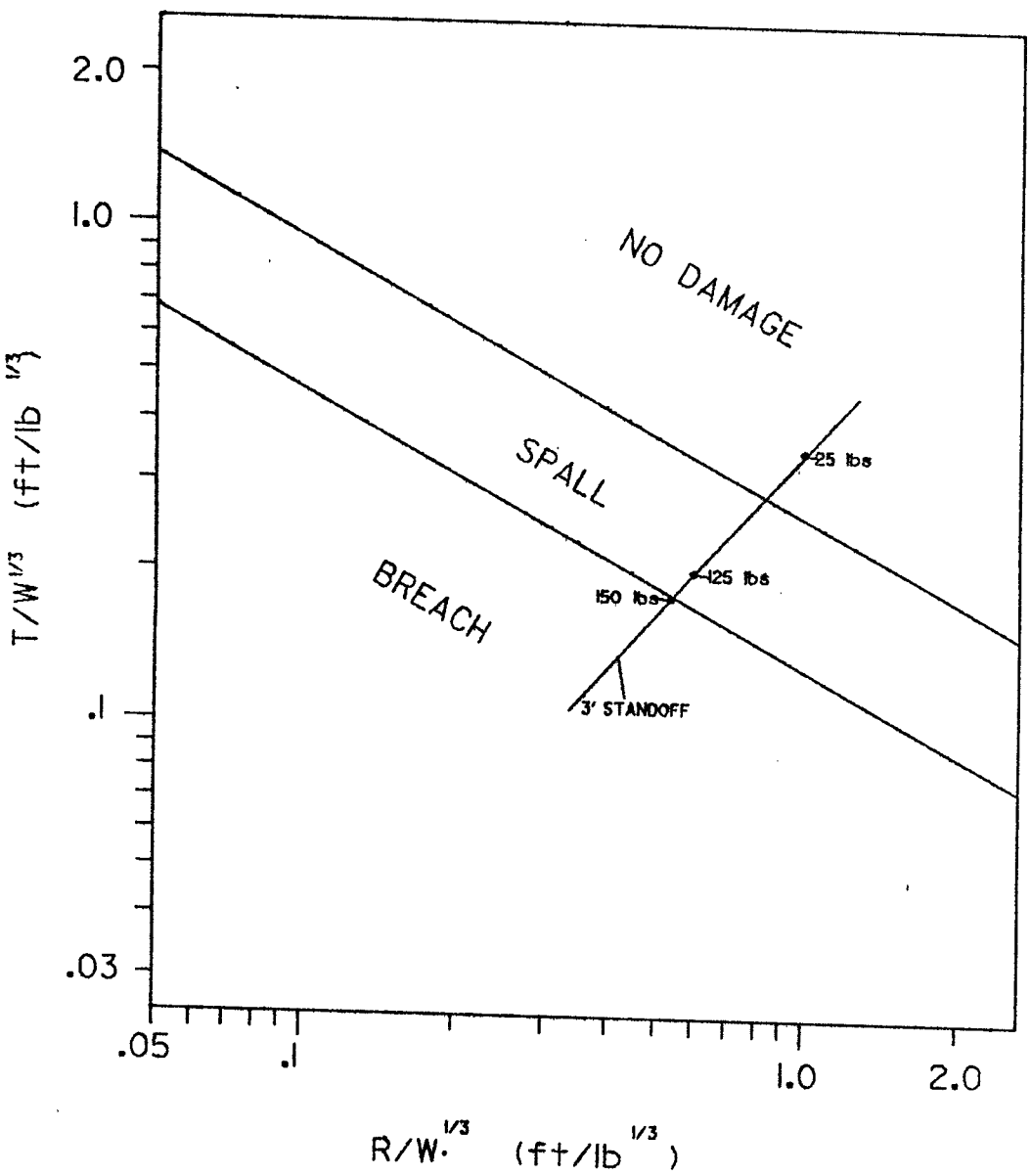
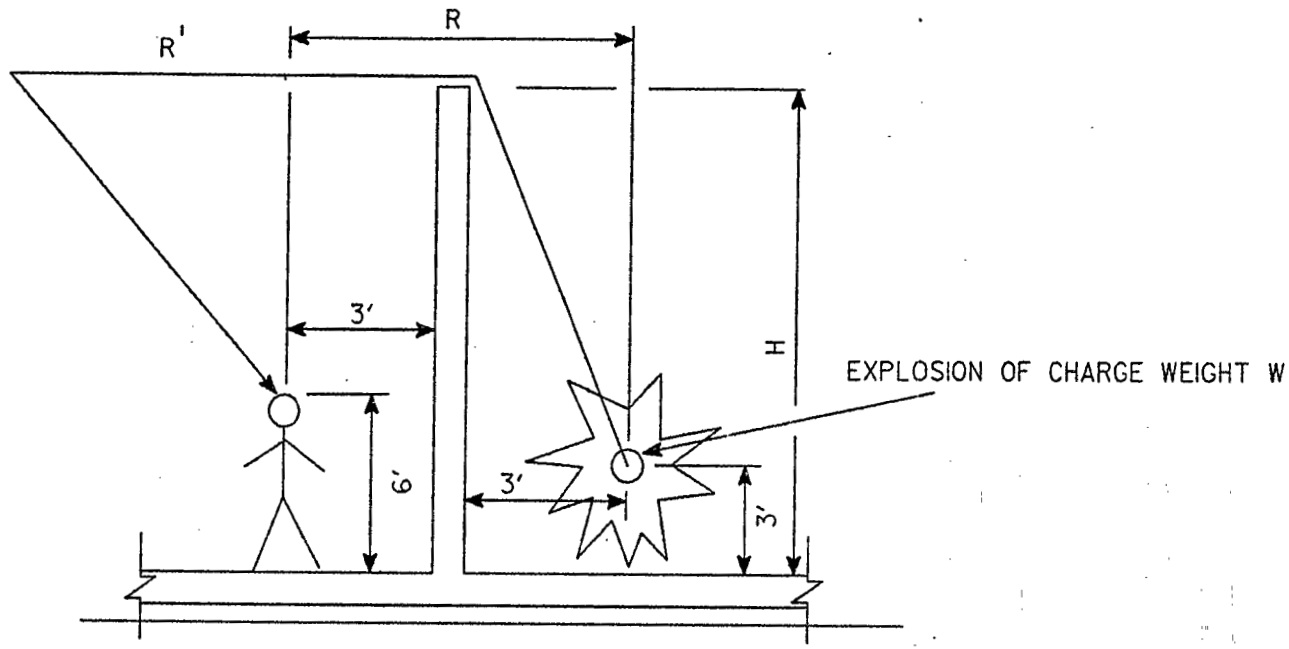


Figure 6 - Spall Damage Chart



W lbs	H ft	R ft	R' ft	$R'/W^{1/3}$ ft/lbs$^{1/3}$	P_{so} psi
5	15	7	39.65	23.18	2.45
	20	7	55.40	32.39	1.45
10	15	7	39.65	18.40	3.33
	20	7	55.40	25.71	2.00
15	15	7	39.65	16.07	4.33
	20	7	55.40	22.46	2.50
20	15	7	39.65	14.60	5.00
	20	7	55.40	20.40	2.90

Figure 7 - Spillover Pressures For Personnel Protection

5 for any particular scaled range. As an example we will use Figure 4 which is for a wall supported on 3 sides. This would be representative of the back wall of a 3 wall cubicle. This figure shows that for a 20 by 20 wall, peak reflected pressures less than 7 psi will never cause wall rotations to exceed 2 degrees regardless of the total impulse. It also shows that for a total reflected impulse less than 250 psi-msec, regardless of pressure, the wall displacement will never exceed 2 degrees rotation. Consider now a 425 lbs explosive donor. For this donor the explosive quantity line crosses the limiting impulse asymptote of 250 psi-msec at a scaled range of approximately 6. This equates to a stand-off distance of about 45 feet. the peak reflected pressure at this distance is about 90 psi. At any stand-off closer than this, the wall will exceed the maximum allowable 2 degree rotation. This demonstrates the discrepancy between the arbitrary 425 lb allowable limit for all storage stand-offs and the approved criteria in reference 2. Now consider a quantity of 25 lbs of explosive. In this case, The explosive quantity line crosses the impulse asymptote at a scaled range of about 2.5. This results in a peak reflected pressure of approximately 1000 psi and the stand-off distance would be about 7 feet. Observations of wall rotation in an actual test of a 9 foot wall recently performed in Reference 6 agree well with this analysis. A general observation from this P-I diagram is that for for the small quantities typically stored in cubicles (less than 425 lbs) the duration of the load will be small with respect to the period of the wall and response will be governed by the impulse capacity. Assuming a typical 3 foot stand-off, the explosive storage limit for a 20 foot square 12 inch wall would be about 20 pounds for structural damage through rotation only. This would be the limit of explosive to prevent incipient failure of the wall as defined by reference 2. We will now evaluate the same wall for spall damage and leakage overpressure to determine the personnel protection limits for the adjacent bay.

Reference 2 and 7 provide methods for estimating the presence of spalling. Based on this approach, several donor quantities at a typical 3 foot stand-off are plotted on Figure 6. This shows that backface spall would begin to occur for a quantity of 25 lbs at a stand-off distance of 2 ft or less. Since spalling would likely generate fragments which would exceed the 58 ft-lb limit, this stand-off is distance is too close to be allowed for personnel protection. The occurrence of spall for this quantity and stand-off agrees reasonably well with recent test data (Reference 6). Reducing to a donor limit of 15 lbs would eliminate the spall risk and result in acceptable protection at the same stand-off. This result is consistent with the quantity allowed in Reference 3 for operational shields.

Last we will look at overpressure and the 2.3 psi limit required by Reference 1. Figure 7 is based on methods given in Reference 8. This procedure is based on test data and estimates an effective range from the Donor to the receiver which empirically accounts for the refraction of the shock waves over the wall. This data indicates that to limit overpressure on a standing operator behind the back wall of a three wall cubicle, the donor explosive limit must be limited to less than 5 lbs for a 15 high ft wall and just under 15 lbs for a 20 ft wall. These estimates assume that the cubicle walls do not extend through the roof of the building. If the walls reached or penetrated the roof, then the spillover pressure would be resisted by the roof over the receiver bay. If this roof was capable of resisting the pressure then the receiver would be protected. If not, then the roof would collapse and become a fragment hazard to the receiver personnel. In this example, without a roof, the requirement of 2.3 psi for personnel protection limits the explosive quantity substantially below the general limit of 15 lbs allowed in reference 3. A comment is appropriate here. The 2.3 psi limit is

considered a threshold value for temporary hearing loss. If the operators were wearing hearing protection, then an overpressure of 5 psi would not pose a significant injury risk considering the short duration and impulse of these quantities. If we consider an overpressure limit of 5 psi, then the explosive limit will lie between 15 and 20 lbs for the 15 and 20 foot walls. The results of this analysis agree well with effects observed in several accidental explosions (References 9-11). This result also agrees well with the general guidance in Reference 3. In any event, the personnel exposure to overpressure is clearly the governing criteria for explosive limits of dividing walls in the configurations considered in this example. For cubicle walls that are cantilever or supported on two sides (a side wall and the floor), the shock wave would also refract around the side wall and this would reduce the allowable explosive limits even further.

CONCLUSIONS

Twelve inch reinforced concrete walls have been given special consideration within DOD explosive safety standards. This consideration recognizes the large number of walls that are in existence and performing a valuable safety function at this time. The 425 lb explosive limit for category IV protection was established based on limited test data. Design criteria for new construction as required by reference 2 would not support such a limit. The 15 lb limit for personnel protection (operational shields) is an acceptable limit for gross wall damage and spalling. Is marginal for overpressure protection at the 2.3 psi level for wall heights less than 20 feet unless they extend through the roof. It is even less conservative for short walls that are cantilever or supported on the floor and one edge.

It is clear that when an existing 12 inch wall is being considered for a new operational function requiring personnel protection, a detailed analysis should be provided to assure its performance.

There is room for differences in interpretation of References 1, 3 and 4. Reference 1 implies compliance with Reference 2 is required. reference 3 limits use to existing facilities. Reference 4 is silent on the subject of such walls in new construction. It is believed that the intent should be for all new construction to comply with Reference 2. It is also believed that the performance of 12 inch walls with 425 lb storage limits should be clearly defined as Category IV. Future revisions of these standards should be coordinated and reconciled.

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